Large strain electrostrictive actuation in barium titanate

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Large strain electrostriction in single-crystal ferroelectric materials is investigated. The mode of electrostriction is based on a combined electromechanical loading used to induce cyclic, 90° domain switching. Experiments have been performed on crystals of barium titanate with constant compressive stress and oscillating electric-field input. Induced strains of more than 0.8% have been measured. Strains as large as 5% are predicted for other materials of the same class. The results demonstrate a possible avenue for obtaining large actuation strains in electromechanical devices. [S0003-6951(00)01137-2]

Ferroelectric ceramics are used in a variety of sensor and actuator applications. In particular, they are one of the basic building blocks of smart structures which have been successfully used for active damping and damage detection. The behavior of conventional materials is characterized by good high-frequency response and low hysteresis, but unfortunately, very small strains (limited to about 0.1%). A variety of methods have been developed for creating large displacement actuators by using monomorph or bimorph benders, functionally graded ceramics, and single crystals. Research on single-crystal ferroelectric materials for sensor and actuator applications have recently focused on exotic relaxor-based systems, formulated near the morphotropic phase boundary, that take advantage of phase transition to produce large actuation strains.[1] The current investigation focuses on the use of domain reorientation to generate a large actuation strain in a ferroelectric single crystal of a simple perovskite structure. Experiments have been performed on barium titanate ($BaTiO_3$), a common ferroelectric, generating strains of more than 0.8%.

The current study is motivated by the theoretical work of Shu and Bhattacharya who developed a model of a ferroelectric single crystal using the setting of finite deformations.[2] They assume the existence of a crystal free-energy density W, which is dependent on the deformation gradient (F), polarization (P), and temperature (θ). For a flat plate configuration with electrodes on two faces, the total energy G can be expressed in three terms consisting of the crystal free-energy density, and external mechanical and electrical work:

$$G(F,P,\theta)=W(F,P,\theta)-E_{\mathrm{o}}\cdot P(\det F)-T_{\mathrm{o}}\cdot F, \qquad (1)$$

where T_{o} is stress and E_{o} is the applied electric field. For a material such as barium titanate, there exist six possible ground states with the polarization vector in one of the six pseudocubic $\langle 100\rangle$ directions. These ground states correspond to multiple energy wells of W. When considering a compressive stress and electric field across the ferroelectric plate, minimization of the total energy results in a phase diagram describing the exchange of stability of the different directions of polarization in the stress–electric-field space. The analysis further suggests that there exists a low-energy path for switching from one polarization to another. Thus, domain polarization can be switched by electric field or applied stress. Furthermore, a combined mechanical and electric loading, consisting of a constant compressive load and variable electric field, can allow cyclic change in the domain pattern. Electric-field-induced domain switching in barium titanate has been studied by a number of researchers.[3,4] Stress-induced domain switching was experimentally demonstrated by Li *et al.*[5] The current study investigates the coupling between stress-induced and electric-field-induced domain switching.

A set of experiments were designed and performed to investigate the possibility of achieving large electrostriction in ferroelectrics using combined electromechanical loading. The experiments were carried out with barium titanate because it is well characterized, easily available, and has a wealth of polarized states. The basic mode of operation, illustrated in Fig. 1, is the following: a thin single-crystal plate, of (100) orientation, is subjected to a constant uniaxial compressive stress and a variable electric field. Since at room temperature barium titanate is spontaneously polarized in the $\langle 100\rangle$ direction, at zero applied voltage the applied stress forces the polarization to be in plane, e.g., the [010] direction. As the voltage is increased, the electric field tries to align the polarization in the [001] direction, but this is resisted by the stress. There is an exchange of stability at a critical voltage and the polarization switches to [001] with an accompanied strain of up to 1.1%. Finally, as the voltage is decreased, the polarization reverts back to in plane, recovering the strain. Thus, as the load is held fixed and the voltage cycled, domain switching provides an electrostriction as large as 1.1%. Strains as large as 5% are predicted for other materials of the same class.[2]

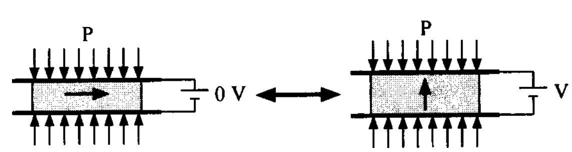

FIG. 1. Mode of operation for large strain electrostriction by domain switching in a tetragonal ferroelectric crystal.

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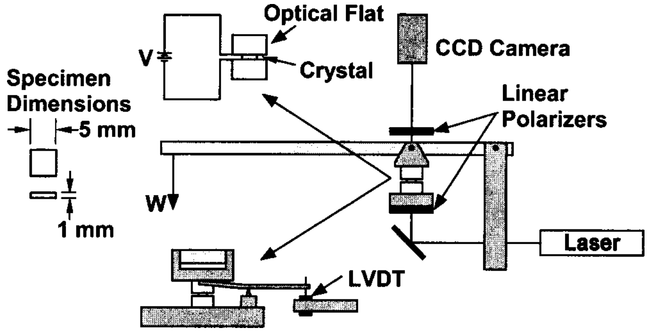

FIG. 2. Schematic diagram of experimental setup for measuring strain response of ferroelectric crystal under electromechanical loading.

An experimental setup, shown in Fig. 2, has been designed to provide a constant stress and variable electric field to a ferroelectric crystal and measure the induced electrostrictive strain. The experimental setup consists of a loading mechanism, displacement measurement transducer, electrodes, and charge-coupled-device camera. The loading mechanism uses dead weight and a lever to deliver a force to a loading frame. The force is transmitted to a pair of optically flat, glass plates that sandwich the specimen. Glass plates are used so that the entire load axis is transparent, allowing direct observation of the specimen during the test. Semitransparent, gold electrodes deposited on the surface of the glass plates are connected to a high-voltage-power amplifier to generate an oscillating electric field across the crystal. The electric field is measured by monitoring the amplifier voltage. The crystal strain is measured by recording the load frame displacement during the course of the experiment, which corresponds to the change in thickness of the specimen. The displacement is measured using a high-resolution linear variable differential transformer (LVDT). A helium–neon laser is used to illuminate the specimen from below. The light passes through crossed polarizers, one below the specimen and one above, and the image is captured on video. This allows observation of domain switching and failure that may occur during the course of the experiment.

Experiments have been performed at different levels of applied stress. Data are shown in Fig. 3 for a compressive stress of 3.6 MPa. The dashed curve is the input electric-field signal with a frequency of 0.05 Hz. The solid curve is the

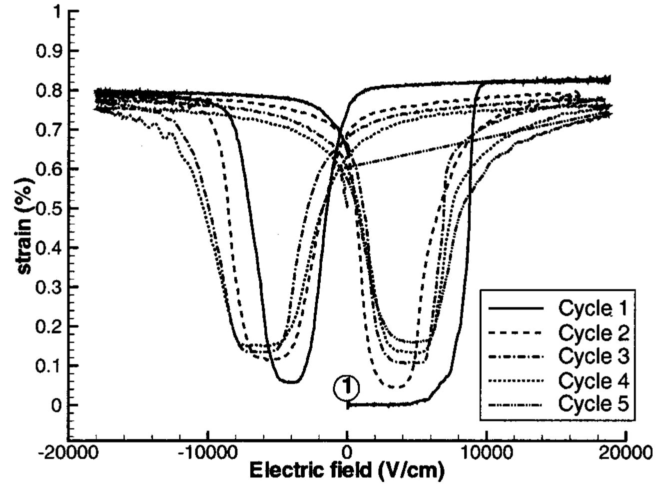

FIG. 4. Strain response as a function of electric field for a barium titanate crystal under a constant compressive stress of 3.6 MPa with a 1/20 Hz sinusoidal input signal.

strain response of the crystal. The same data are shown in Fig. 4 with strain as a function of the electric field. All strains are relative to the initial configuration. The experiment begins at point 1 with the strain increasing linearly with the electric field. At about 6000 V/cm, the strain begins to rapidly increase until the electric field reaches about 10 000 V/cm, at which point the strain levels off. The strain again increases linearly to a maximum strain of about 0.83%. As the electric field is decreased, the strain decreases linearly until the electric field reaches about 1200 V/cm. The strain then decreases rapidly as the electric field reaches zero and the polarity is reversed. The minimum strain is reached at an electric field of about -3600 V/cm, although the entire 0.83% strain is not recovered. As the magnitude of the electric field is increased (with negative polarity), the strain value again increases in a similar manner as before with a slightly lower value of maximum strain. The minimum strain is reached after the electric field passes through zero at about 2600 V/cm. Subsequent cycles proceed in a similar manner, although with degraded performance. The data for this experiment end halfway through the fifth cycle, at which point arcing occurs.

Figure 5 shows the strain envelope, i.e., the difference between the maximum and minimum strain in each cycle, as

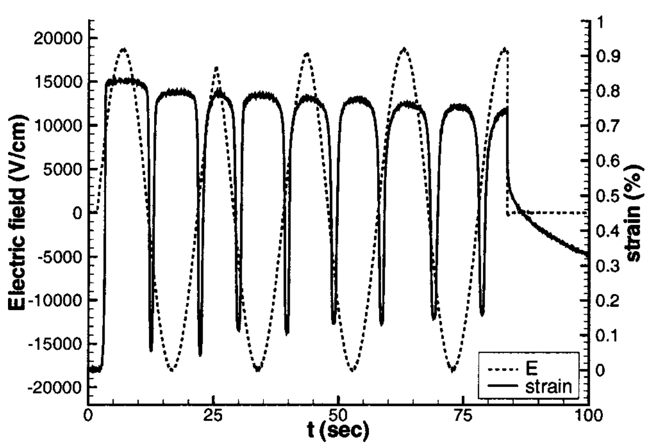

FIG. 3. Electric-field input signal and strain response as a function of time for a barium titanate crystal under a constant compressive stress of 3.6 MPa.

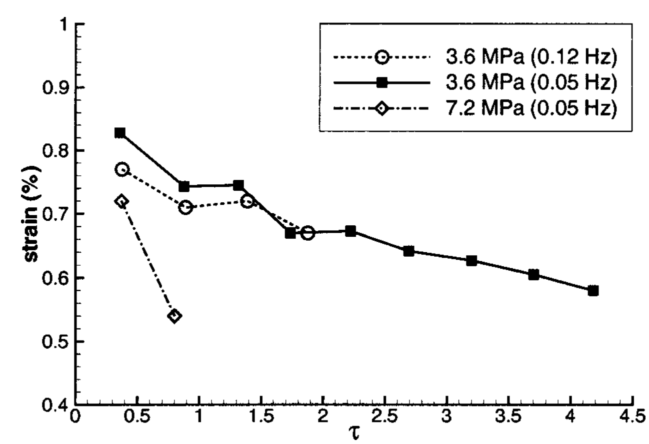

FIG. 5. Strain envelope (difference between maximum and minimum strain for a given half cycle) as a function of normalized time for three different experiments and two stress levels.

a function of normalized time τ (time/period of input signal). Data are shown for three experiments at two different stress levels. The top curve is for the case mentioned in the previous paragraph with a stress of 3.6 MPa and an input frequency of 0.05 Hz. The middle curve is for an experiment with the same stress with an input frequency of 0.12 Hz. The lower curve is for a stress of 7.2 MPa and an input frequency of 0.05 Hz. In each case, the maximum strain is obtained during the first cycle with the level decreasing with each subsequent cycle. The maximum strain is less than the theoretical maximum of 1.1%, indicating that complete domain switching does not occur in any of the cases. This may be because domains near the loaded surfaces of the crystal are unable to switch due to friction. The reduction of the strain envelope with ensuing cycles is most likely due to accumulation of damage in the crystal, i.e., the formation of cracks.

The experiments have demonstrated that barium titanate can generate electrostrictive strains of 0.8% when subjected to suitable coupled electromechanical loading. This offers an avenue for generating large actuation strains that can be extended to other ferroelectric crystals. Indeed, we predict that strains as high as 5% can be obtained in other materials.[2] A number of issues need to be addressed, however, before applications of this method can be pursued; most notably, the quick degradation of the strain response. This problem is related to the mechanical and electrical boundary conditions, including friction and the choice of electrode material,[6] as well as the presence of defects in the material. The use of more suitable electrode materials may be helpful in delaying the degradation of the crystal. Indeed, preliminary experiments using platinum electrodes (instead of gold) have shown significant improvement. Further improvement may be possible with conductive metal–oxide electrodes which have been successfully used to extend the fatigue life of ferroelectric memory.[6] *In situ* studies of the interaction of domain walls with defects, such as vacancies and preexisting cracks, will also be useful. These issues and their influence on the failure modes are being pursued and will be reported in the future.

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